Human eyes are capable of six types of movement: x/y lateral shifts, z levelling, horizontal and vertical rotations, and cyclotorsion (rotation around the optical axis). Current laser technology for refractive surgery creates corneal alterations to correct refractive errors more accurately than in the past. Ablation profiles are based on the removal of tissue lenticules through sequential laser pulses that ablate a small amount of corneal tissue to compensate for refractive errors. However, the quality of vision after laser refractive surgery can deteriorate significantly, especially under mesopic and low-contrast conditions.

The induction of optical aberrations, such as spherical aberration and coma, are related to loss of visual acuity and quality. To balance existing aberrations, customized treatments have been developed using either wavefront measurements of the whole eye obtained with Hartmann-Shack wavefront sensors or corneal topography-derived wavefront analysis. Topography-guided, wavefront-driven, wavefront-optimized, asphericity-preserving, and Q-factor-based profiles have been advanced as solutions to address aberrations.

Schwiegerling and Snyder measured eye motion in patients undergoing LASIK using a video technique to determine centration and variance of the position of the eye during surgery. They found a standard deviation in eye movements in all eyes of greater than 100 µm. Taylor et al determined the accuracy of an eye-tracking system designed for laser refractive surgery; the system demonstrated an accuracy of 60 µm for an intact cornea and 100 µm for a cornea with a thin flap removed.

Bueeler et al investigated the lateral alignment accuracy needed in wavefront-guided refractive surgery to improve the optics to a desired level in a percentage of normally aberrated eyes. To achieve the diffraction limit in 95% of normal eyes with a 7-mm pupil, a lateral alignment accuracy of 70 µm or better was required. An accuracy of 200 µm was sufficient to reach the same goal with a 3-mm pupil.

Bueeler and Mrochen quantified the parallax error associated with localizing corneal positions by tracking the subjacent entrance pupil center by means of optical ray tracing in a schematic model eye. They found that tracking error can amount to 30% of the detected lateral shift (or more for eye trackers mounted closer than 500 mm to the eye). Thus, if the eye tracker registers a lateral shift of the entrance pupil of 200 µm away from the tracking reference axis, the point of interest located on the cornea would essentially be 260 µm away from this reference axis. A laser pulse fired at that moment would be systematically displaced by 60 µm.

Measuring rotation when the patient is upright but performing the refractive treatment when the patient is supine may lead to ocular cyclotorsion, resulting in mismatching of the applied versus the intended profiles. Recent technologies, such as the Amaris Total-Tech laser (Schwind eye-tech-solutions, Kleinostheim, Germany), can facilitate measurement of and potentially compensate for static cyclotorsion that occurs when the patient moves from the upright to the supine position during the procedure by quantifying the cyclorotation occurring between wavefront measurement and laser refractive surgery and compensating for it. Further, measuring and compensating for ocular cyclotorsion during refractive treatments with the patient supine may reduce optical noise of the applied versus the intended profiles.

Although many studies have discussed the implica-
DIMENSIONS OF EYE MOVEMENT

Lateral movements during ablation (first and second dimensions). The eye tracking system of the Amaris Total-Tech laser includes a number of modules to keep track of different types of eye movements. In a pupil-registration module for the eye-tracker subsystem, the first pupil image obtained by the Amaris system when the ablation begins is taken as a reference, and its location in reference to the limbus is used for any further eye-tracker image in order to determine the pupil center shift compensation.

Eye rolling during ablation (third and fourth dimensions). In the scleral-registration module for the eye-tracker subsystem, the first few scleral-tracker images obtained when the ablation begins are taken as reference for natural rolling and compared to any further scleral-tracker image to determine eye rolling.

Static cyclotorsion between upright and supine positions (fifth dimension). In the eye-registration module for the eye-tracker subsystem, the diagnostic image is used as a reference and compared to an eye-tracker image obtained by the Amaris system before ablation begins in order to determine the static cyclotorsion component.

Dynamic cyclotorsion during ablation (fifth dimension). In the eye-registration module for the eye-tracker subsystem, the first eye-tracker image obtained by the Amaris system after ablation begins is taken as reference and compared to any further eye-tracker image in order to determine the dynamic cyclotorsion component (DCC).

Axial displacement during ablation (sixth dimension). The scleral-registration module for the eye-tracker subsystem also uses the first few scleral-tracker images obtained after ablation begins as reference for the natural level; this is compared with any further scleral-tracker images to determine axial displacement.

COMPENSATION FOR OCULAR CYCLOTORSIONS

Using these measurements, the Amaris Total-Tech laser compensates for any ocular cyclotorsions that occur from the upright to supine position (static cyclotorsion from diagnosis to treatment), as well as lateral movement, eye rolling, dynamic cyclotorsion, and displacements along the propagation axis that happen during laser treatment. Additionally, the Total-Tech laser compensates for differences in pupil size and pupil center.

TAKE-HOME MESSAGE

- The Total-Tech laser can facilitate measurement of and compensate for static cyclotorsion that occurs when patients move from the upright to the supine position.
- Measurements of the six-dimensional movements of the eye can be used to compensate for both static and dynamic conditions during laser corneal ablation.
during treatment compared with measurements at the time of diagnosis because the theoretical impact of cyclorotated ablations is smaller than those of decentred ablations or edge effects (coma and spherical aberration). In this way, additional lateral displacements due to cyclotorsions that occur around any position other than the ablation center are avoided. (Induced aberrations emanating from lateral displacements always increase with decentration.)

**EYE TRACKING IN SIX DIMENSIONS**

A six-dimensional eye-tracker is important because uncompensated movements can result in unwanted aberrations. Uncompensated lateral pupil movements induce decentrations that can manifest as coma-like aberrations. Uncompensated rolling movements also induce decentrations that can manifest as coma-like aberrations. Uncompensated cyclotorsional movements can induce aberrations, whereas uncompensated axial movements can induce asymmetrical undercorrections. Axial movements can result in laser spots that are no longer in focus when they reach the cornea, reducing the radiant exposure and the ablation depth of the spot. Axial movements can also produce pulses that hit the cornea more centrally than planned if the eye moves towards the laser system and more peripherally if the eye moves away from the laser.

**RESULTS**

In our experience, the average pupil displacement as measured with the Amaris system was 150 µm. Three percent of eyes had pupil displacements exceeding 1 mm. The range of pupil displacements over the treatment was relatively mild, with peaks of about 1.5 mm. The average amount of rolling movement was 5°. This value happens to be the most commonly accepted value for natural rolling, measured as angle alpha, lambda, or kappa. In 3% of eyes, rolling exceeded 8°. The range of rolling movements over the treatment were relatively mild, with peaks of up to about 10°.

The average static cyclotorsional error was 1°, which was lower than the observations of Ciccio et al, who reported 4° (Figure 4). In 3% of eyes, cyclotorsion exceeded 8°. The mean DCC values over the treatment were relatively small, but with peaks of up to approximately 5°. Considering that the average cyclotorsion from the upright to the supine position is about ±4°, it is not enough to compensate only for the static cyclotorsion without considering the dynamic cyclotorsion during the laser procedure. The effects of the DCC can be considered as optical noise of the applied versus the intended profiles.

Without eye registration technologies, considering that maximum cyclotorsion measured between the upright and supine positions does not exceed ±14°, this explains why classical spherocylindrical corrections in refractive surgery succeed without major cyclotorsional considerations. However, only limited amounts of astigmatism can effectively be corrected with this amount of cyclotorsional error.

Currently available eye registration technologies, which provide an accuracy of about 1° and measure static and dynamic cyclotorsion components, have introduced a new era in corneal laser refractive surgery because patients may be treated for a wider range of refractive problems with enhanced success. High-resolution ablation systems are also required.

Measuring axial movement, we obtained an average of -300 µm. This negative value, which is fairly low, means that some patients push their head back at the beginning of the treatment and return closer to level during treat-
CONCLUSIONS

In our experience of over 8,000 eyes treated with the Amaris Total-Tech laser, 91% of treatments resulted in a postoperative cylinder within 0.50 D of target, and 19% of eyes gained lines of BCVA from baseline. From the minor induction of aberrations, it can be inferred that mesopic and low-contrast visual acuity have maintained their best corrected preoperative levels. More clinical data are required to accurately gauge how much improvement can be expected from the use of this technology.

We have found that the Total-Tech laser’s six-dimensional eye-tracker yields excellent outcomes that are safe and predictable. Refractions are reduced to subclinical values, with 70% of eyes achieving within ±0.25 D of emmetropia and 19% gaining lines of BCVA (mean postoperative defocus, −0.12 ± 0.17 D; astigmatism, 0.15 ± 0.25 D). Rate of registration is greater than 90% for cyclotorsion and greater than 80% for rolling and axial movements. Mean rolling was within ±5° in 52% of cases, dynamic rolling was within ±5° in 66% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic rolling was within ±5° in 52% of cases, static cyclotorsion was within ±5° in 52% of cases, dynamic moving was within ±0.5 mm in 69% of cases, and dynamic cyclotorsion was within ±0.5 mm in 69% of cases.

Six-dimensional movements of the eye can be effectively measured, and these measurements can be used to compensate for both static and dynamic conditions during laser corneal ablation with the Amaris Total-Tech laser.

Maria Clara Arbelaez, MD, practices at the Muscat Eye Laser Center, Muscat, Sultanate of Oman. Dr. Arbelaez states that she has received travel fees from Schwind eye-tech-solutions. She may be reached at tel: 96824691414; fax: 96824601212; e-mail: drmaria@omantel.net.om.

Samuel Arba-Mosquera, MSc, is an Optical/Visual Researcher at Schwind eye-tech-solutions, Kleinostheim, Germany. Mr. Arba-Mosquera may be reached at tel: +49 6027 508 274; fax: +49 6027 508 520; e-mail: samuel.arba-mosquera@eye-tech.net.